An Analysis of the **TOPEX/Poseidon** Operational orbit:

Observed Variations and Why*

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Following launch on 10 August 1992, TOPEX/Poseidon began and continues a very successful global study of the earth's ocean circulation using a combination of radar altimetry and precision orbit determination. TOPEX/Poseidon is a joint effort of NASA and the French Space Agency CNES (Centre National d'Etudes Spatiales) and is currently in the final year of its three-year primary mission. A three-year extended mission phase will follow. The near-circular frozen orbit has a mean altitude of ~1336 km and an inclination of ~66 deg, providing a repeat ground track covering 127 orbits over ~10 days. Periodic orbit maintenance maneuvers (OMMs) keep the ground track within ±1 km of a reference ground track, while also ensuring that other orbital parameters remain within required limits. Precision orbit determination (POD) performed by the Goddard Space Flight Center (GSFC) using laser ranging and DORIS tracking data (CNES) defines radial position relative to the geocenter to an unprecedented accuracy of ~5 cm.

The POD results are utilized to reconstruct the operational orbit history in terms of classical mean elements. The key parameters are the semi-major axis $a$, the inclination $i$, and the eccentricity vector, $e$-$\omega$. These mean elements reflect removal of all central and third-body perturbations having periodic variations over a single ground track repeat cycle. A 20x20" truncation of the JGM2 earth gravity field determines the mean semi-major axis relative to the POD to an RMS accuracy of ~14 cm; determines mean inclination to an RMS accuracy of ~5 $\mu$deg, and determines the eccentricity vector parameters with an RMS of ~9 deg for $\omega$, and ~7 ppm for eccentricity. This paper defines the mean elements, determines their computational precision and cost, and establishes the sources of their variation. The effects of these variations on the ground track behavior are then summarized.

Semi-major Axis

Pre-launch studies indicated ground track control could be effectively provided by periodic removal of accumulated semi-major axis decay caused by along-track forces due almost entirely to atmospheric drag. This control process requires sub-meter semi-major axis determination accuracy, achieved by operational orbit determination performed by the GSFC Flight Dynamics Facility using one-way Doppler acquired via the NASA Tracking and Data Relay Satellite System (TDRSS). The rate of semi-major axis decay would depend primarily on the 81-day mean $F_{10.7}$ solar flux. At launch in August 1992, the mean solar flux was ~125x10$^{-22}$ watts/m$^2$/Hz and has steadily declined from this level as the minimum of solar cycle 22 approaches, currently expected in late 1996. These circumstances limit the drag-induced semi-major axis decay rate to ~5 to 7 cm/day.

After launch, observed changes in semi-major axis were much larger than expected, indicating the presence of additional along-track forces, now confirmed to have body-fixed origins. These forces cause either orbital boost or decay, depending on the yaw control mode. Either sinusoidal yaw steering or fixed yaw modes maintains nadir pointing for altimetry and points the large 28 m$^2$ solar array (SA) near the sun for power management. The body-fixed forces arise from solar radiation, thermal gradients, and molecular outgassing, produced mostly by the large SA, particularly during a fixed yaw mode. Shortly before launch, a plan was adopted to use a SA pitch bias to limit peak battery charge currents during exit from earth occultation. A 54-deg pitch bias effectively regulates battery performance, but radiation forces normal to the SA are not along the sunline as originally planned and reflected throughout navigation software. As a result, sizable unplanned along-track components accumulate to change the semi-major axis as much as 25 cm/day, the direction and magnitude depending on the yaw mode. These body-fixed forces can either offset or add to the decay in semi-major axis induced by atmospheric drag (Fig. 1). Estimates of these forces and an effective prediction model were needed to maintain the satellite orbit and ground track.

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The combined effects of atmospheric drag and the body-fixed forces on semi-major axis were effectively estimated from quick-look orbit determination based on laser ranging data. A byproduct of this strategy is the total once/rev along-track non-gravitational acceleration from which the total rate of change in semi-major axis can be easily computed. Isolation of the body-fixed forces then requires removal of drag contributions. The integrity of this process depends on the accuracy of the atmospheric density model, and this always raises reasonable concern. This paper compares the performance of the Jacchia-Roberts and DTM empirical density models, neither of which reflects flight data at TOPEX/Poseidon altitude. Theoretical models of the body-fixed forces were developed for each yaw control mode using estimates of satellite surface properties and inflight temperature measurements. Differences between the theoretical models and observed data are currently most notable during yaw steering when SA curling caused by thermal imbalances are believed to be the primary contributor to observed along-track forces. Ongoing improvements in the theoretical models may eventually permit their operational use instead of the more complex and tedious empirical techniques currently used. Such modeling improvements may simplify flight operations and allow more confident isolation of drag contributions that could lead to improved density models.

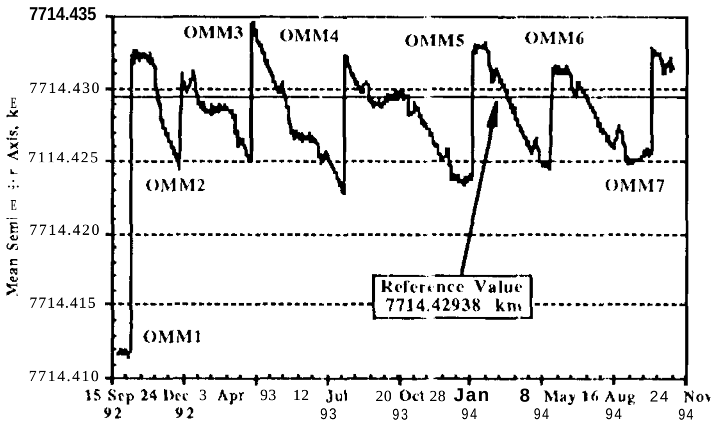


Fig. 1. Mean Semi-major Axis History

inclination

An orbit inclination of ~66 deg allows coverage of ~95% of the earth's ice-free oceans, while also providing the first-ever measurements of ocean tides from space. The required "target" inclination of 66.0408 deg provides precise overflight of two ground verification sites during each repeat cycle, determined by removing all gravitational perturbations with periods up to three years (prime mission duration). The mean inclination, defined by removal of only the perturbations with 10-day periodicity, exhibits long-term variations of ±3 mdeg about the target value due to a combination of lunar and solar gravity influences. Lunar gravity alone induces the shorter-term variations (see Fig. 2). At TOPEX/Poseidon altitude, these perturbations induce ground track variations of similar magnitude as caused by either atmospheric drag or the body-fixed forces. The effects of lunar-solar gravity on the ground track become more pronounced in the presence of lower drag as the solar minimum approaches in late 1996.

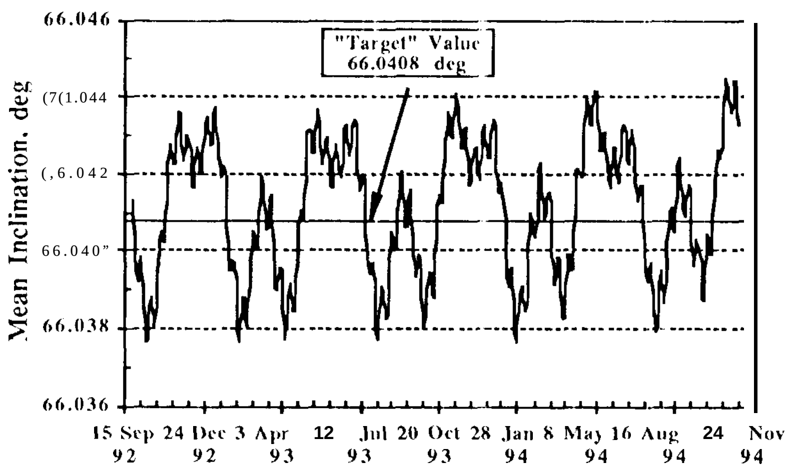


Fig. 2. Mean inclination History

## Eccentricity Vector

Usc of a frozen orbit limits variations in eccentricity and periapse location and precludes the need for ma ncu vers specifically dedicated to their cent ml. An eccentricity $e < 0.0001$ suitably limits altitude variations for effective altimetry. A frozen orbit easily guarantees this control by the near-cancellation of higher-order geopotential perturbations on $\omega$ by secular variations, while lowcl-order perturbations On eccentricity vanish when $\omega = 90$ or 270 deg. A sequence of six orbit acquisition maneuvers achieved eccentricity vector values mar the target conditions of $e = 95$ *ppm* and $\omega = 90$ deg. Fig, 3 shows that inflight variations in $e$ and $\omega$ during the two years since launch systematically vary about these target values. The paper explains these variations and the influence of ongoing OM Ms, and compares them with those predicted by pre-flight studies.

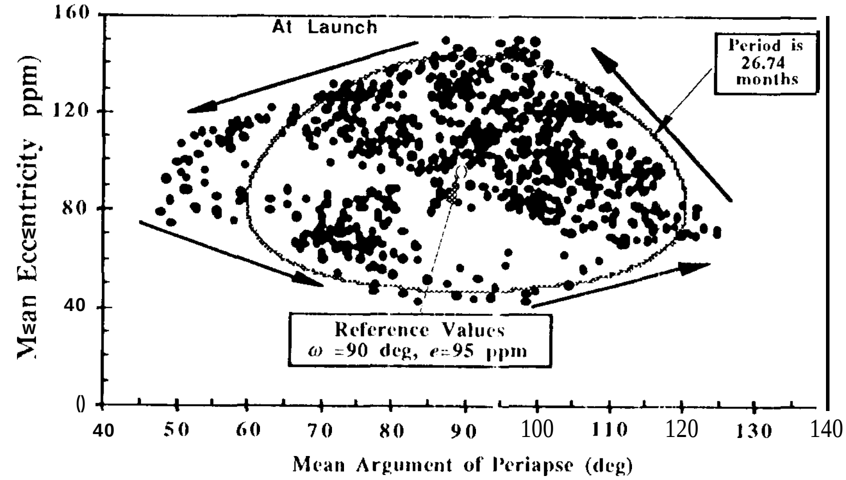


Fig. 3. Eccentricity Vector History

## Ground Track History

Since precisely achieving operational orbit conditions during the first six weeks following launch, there have been seven OM Ms implemented to effectively maintain the satellite ground track within $\pm 1$ km of the reference ground track. These OM Ms, performed near the cast boundary of the control band, raise the decayed semi-major axis above the reference value (see Fig. 1), thereby inducing a westward drift in the ground track. Fig. 4 shows the resulting ground track history and each OM M location. Lunai -solar gravity perturbations induce short-term periodic oscillations in the orbit node and node rate, and have the most pronounced effect as the ground track mars the west boundary. These perturbations have the same order of magnitude effect on the satellite ground track as either atmospheric drag or the body-fixed forces, and can therefore greatly influence ground track behavior. The paper relates these ground track variations to those observed in the classical mean elements.

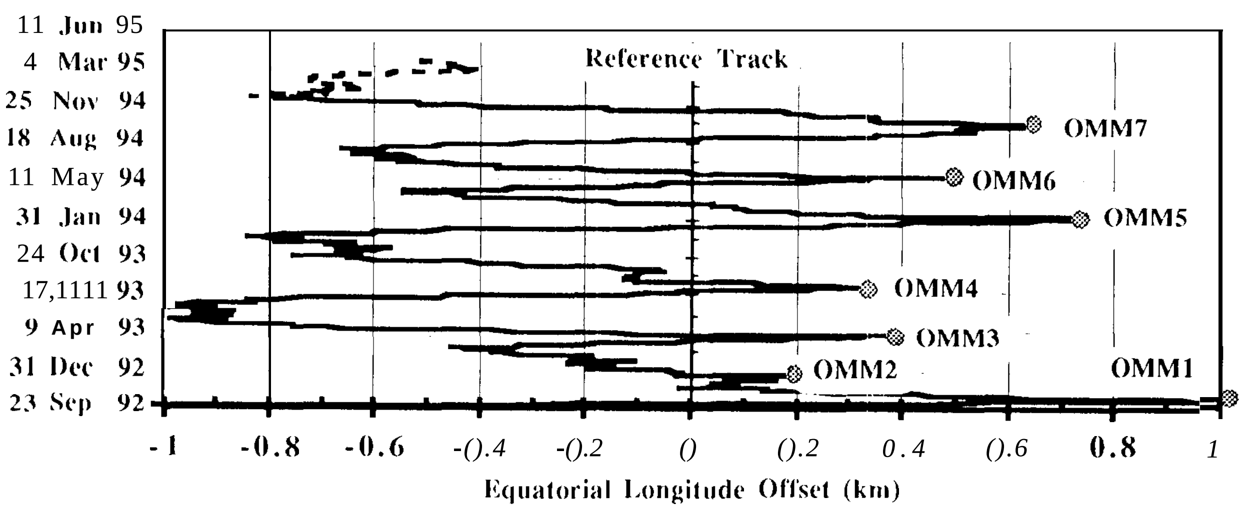


Fig. 4. Ground Track History and Related Orbit Maintenance Maneuvers (OMMs)